

# Opportunities for Exploring Longitudinal Dynamics in Heavy Ion Collisions at RHIC

RIKEN BNL Research Center Workshop  
January 20-22, 2016 at Brookhaven National Laboratory



## Workshop Summary



Sean Gavin

Wayne State University

# Opportunities for Exploring Longitudinal Dynamics in Heavy Ion Collisions at RHIC



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What is the nature of the initial state and how does it evolve in rapidity?  
How does hydrodynamic flow arise?  
How do hydrodynamic fluctuations and dissipation influence its evolution?  
How is energy, momentum and baryon number transported to mid-rapidity?

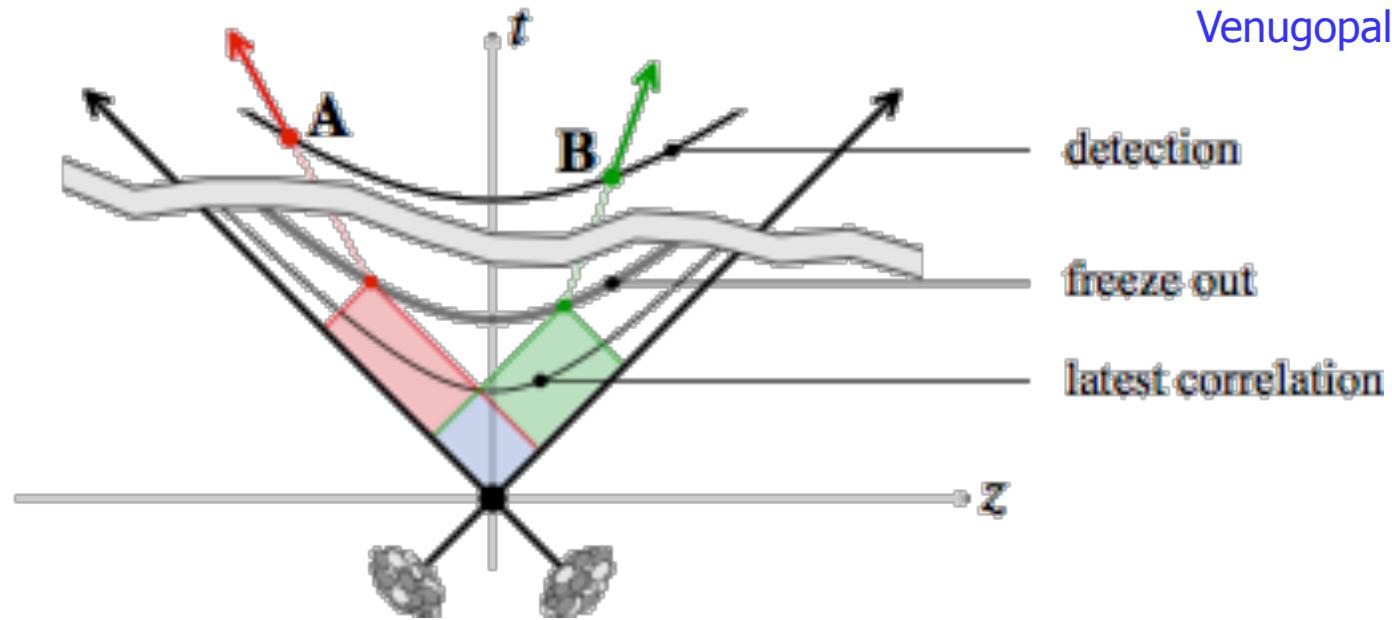


# Rapidity is Different

Bjorken, Lect. Notes in Phys. 56 (Springer, 1976) p. 59; PRD 27, 140 (1983)

Shuryak, Phys. Lett. 78B, 150 (1978)

from Raju  
Venugopalan



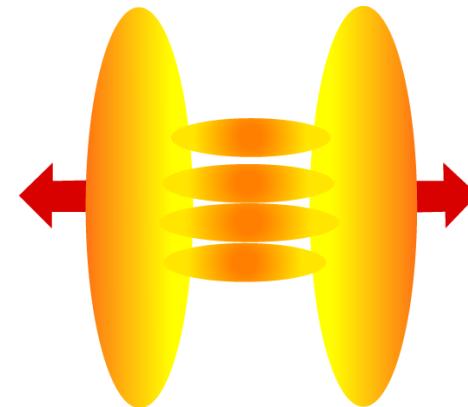
- longitudinal 1d Hubble like expansion
- rapidity separation  $\rightarrow$  time of last correlation

# Rapidity Correlations

Longitudinal fields initially

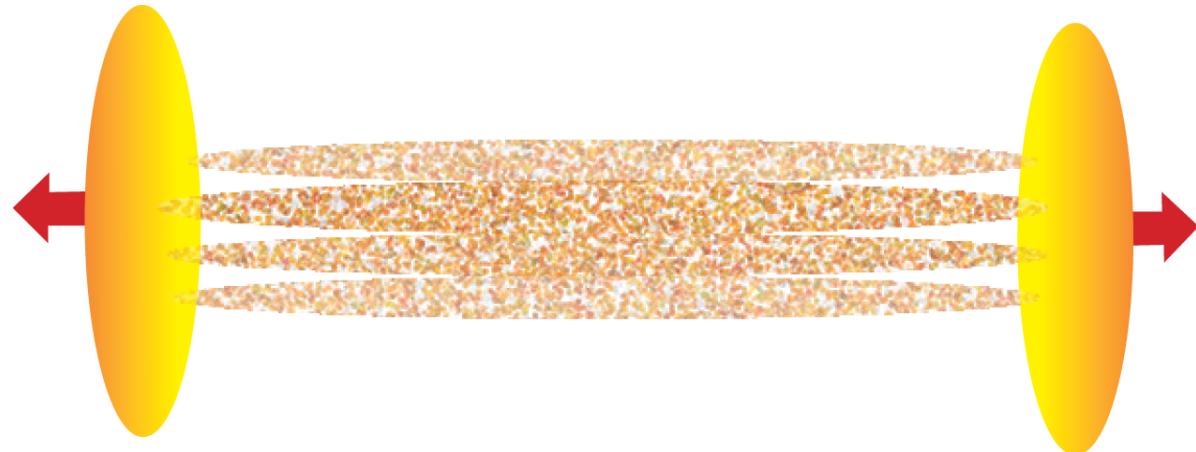
Fields → gluons + quarks  
at ~ fixed proper time

$$\tau_0 > 2R / \gamma$$



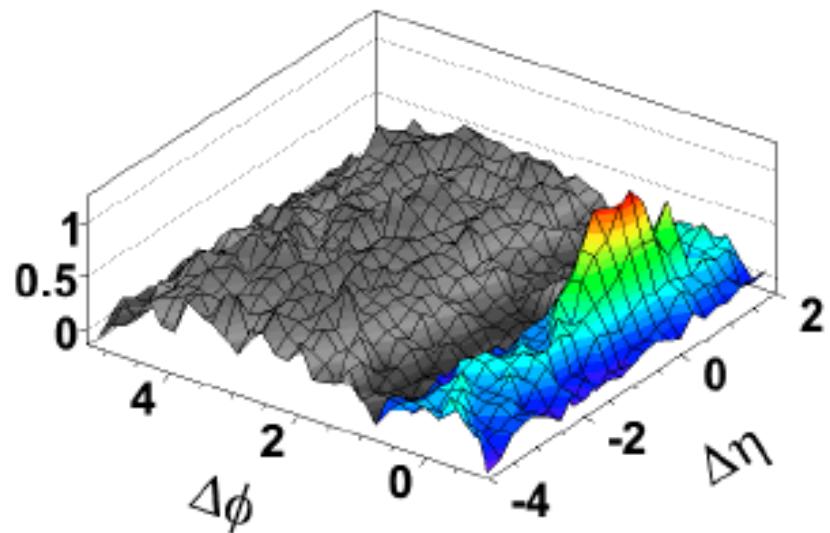
**short range:** pairs  
nearby in rapidity  
evolve together

$$\Delta y < \lambda_{mfp} / \tau_0$$



**long range:** larger  $\Delta y$  pairs – correlated only by production mechanism

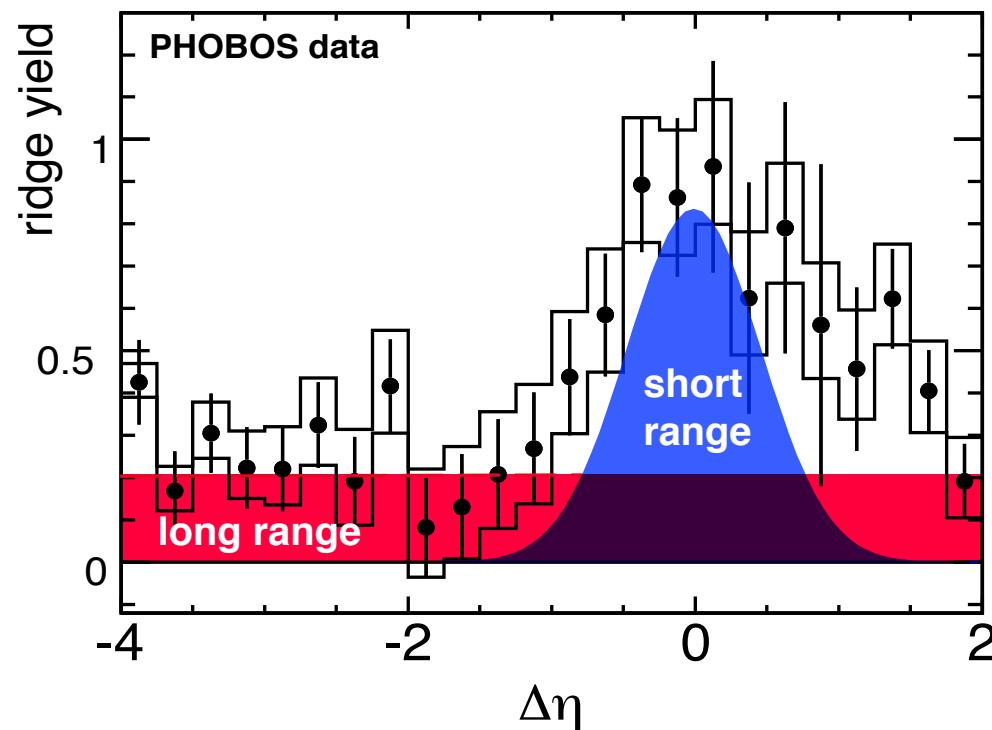
# Short and Long Range Correlations



**ridge:** near side  
in azimuthal  $\Delta\phi$

**flow:** away side  
 $\Delta\phi$  harmonics

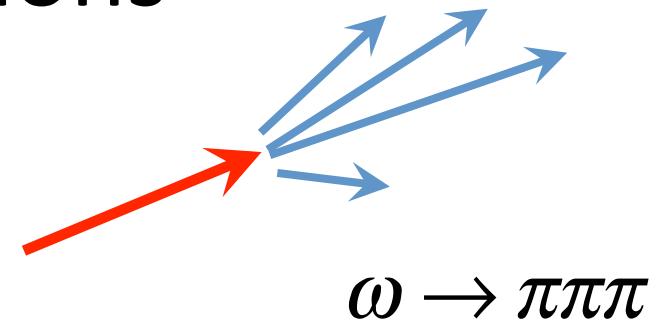
$p_T^{\text{trig}} > 2.5 \text{ GeV}/c$   
 $p_T^{\text{assoc}} \geq 20 \text{ MeV}/c$



# Sources of Correlations

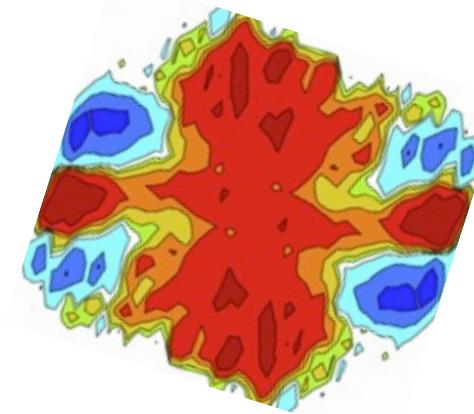
## Short range correlations

- HBT
- Jets
- Resonances
- Phase Transitions
  - see Yi Yin's talk



## Long range correlations

- Flux tubes
- Baryon Stopping
- Conservation Laws



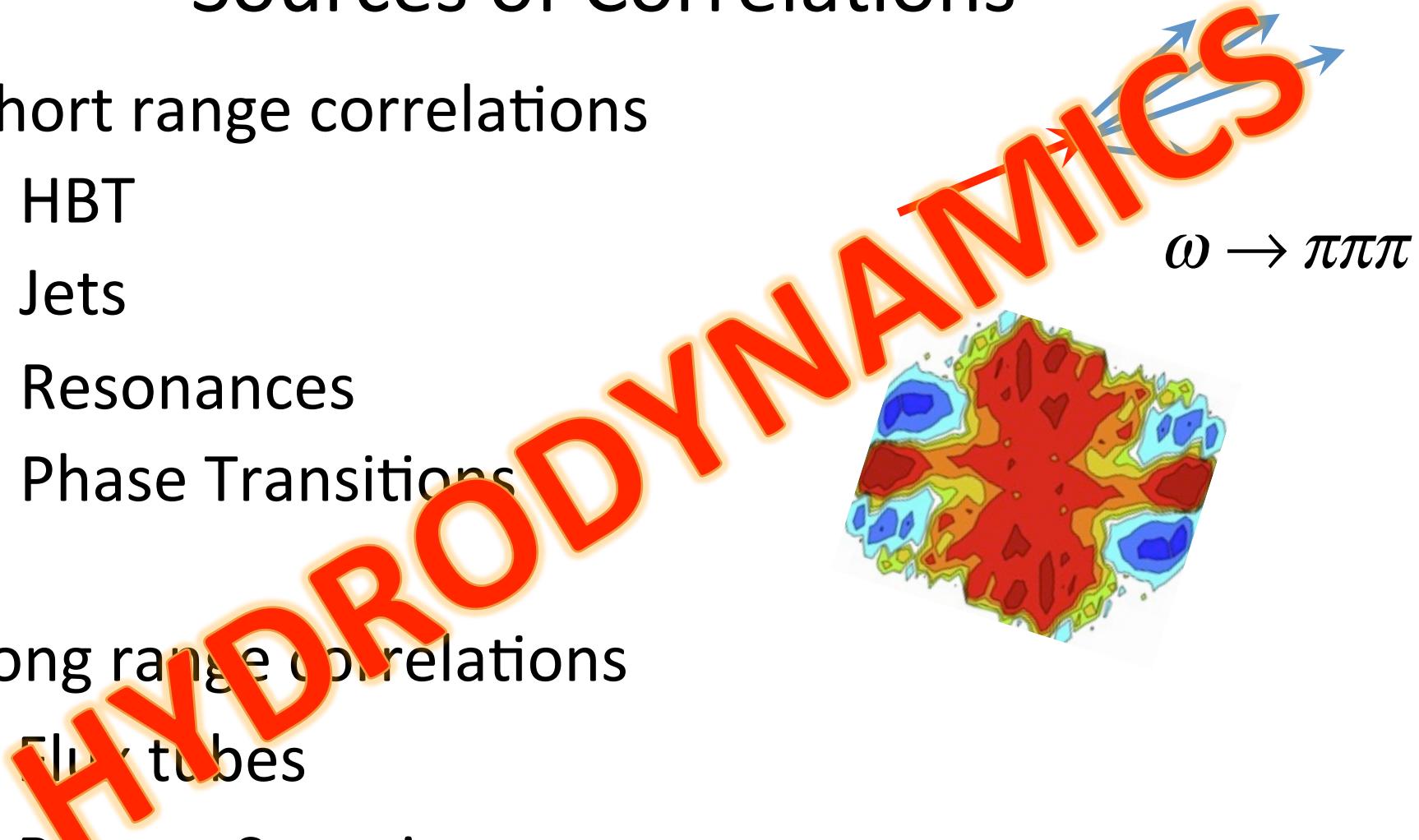
# Sources of Correlations

Short range correlations

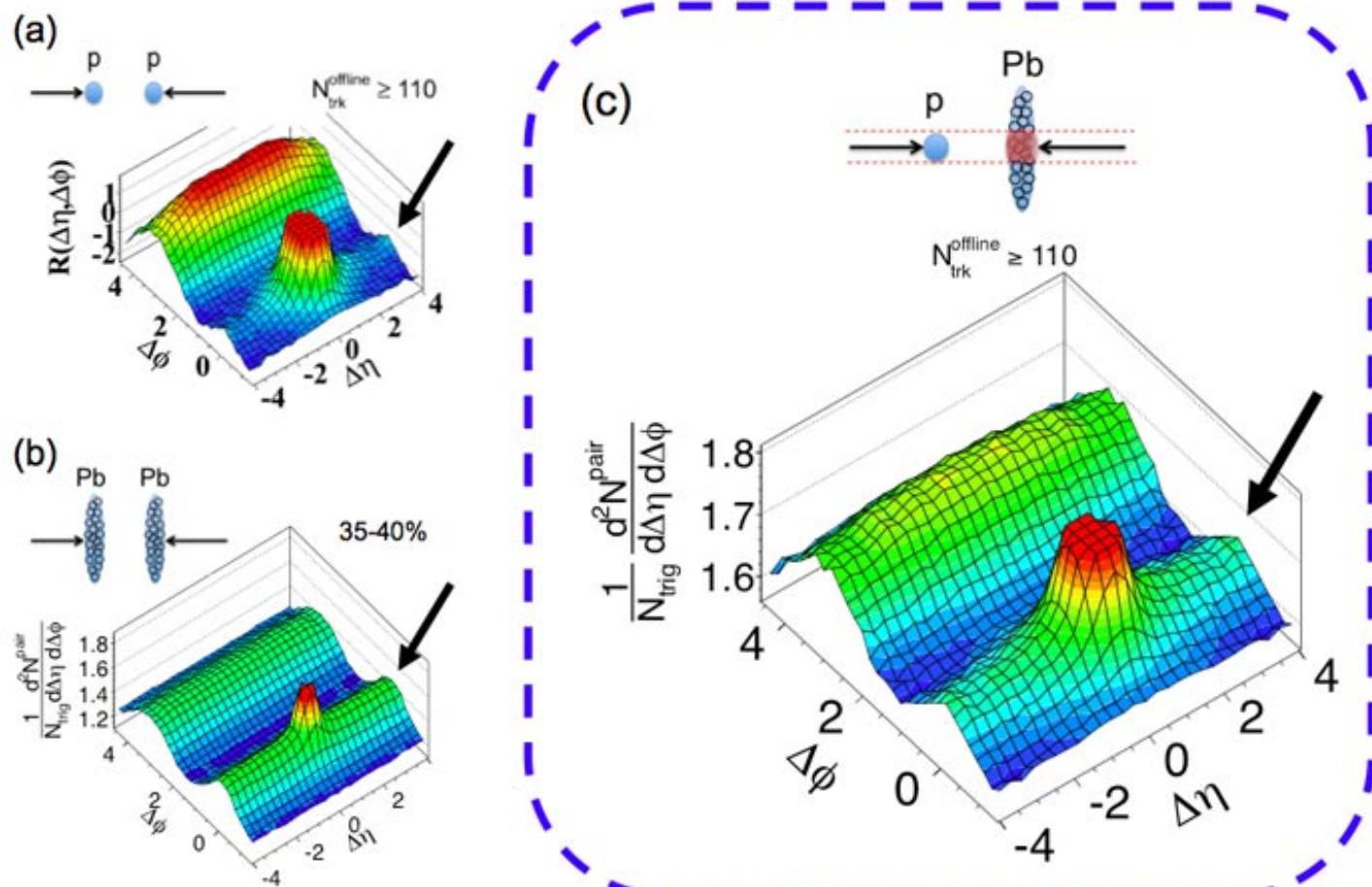
- HBT
- Jets
- Resonances
- Phase Transitions

Long range correlations

- Flux tubes
- Baryon Stopping
- Conservation Laws



# Can Correlations Probe the Origin of Hydrodynamics?



# Origin of Flow: Issues

- GLASMA, pQCD contributions to early flow and flow observables

**Fries, Mäntysaari**

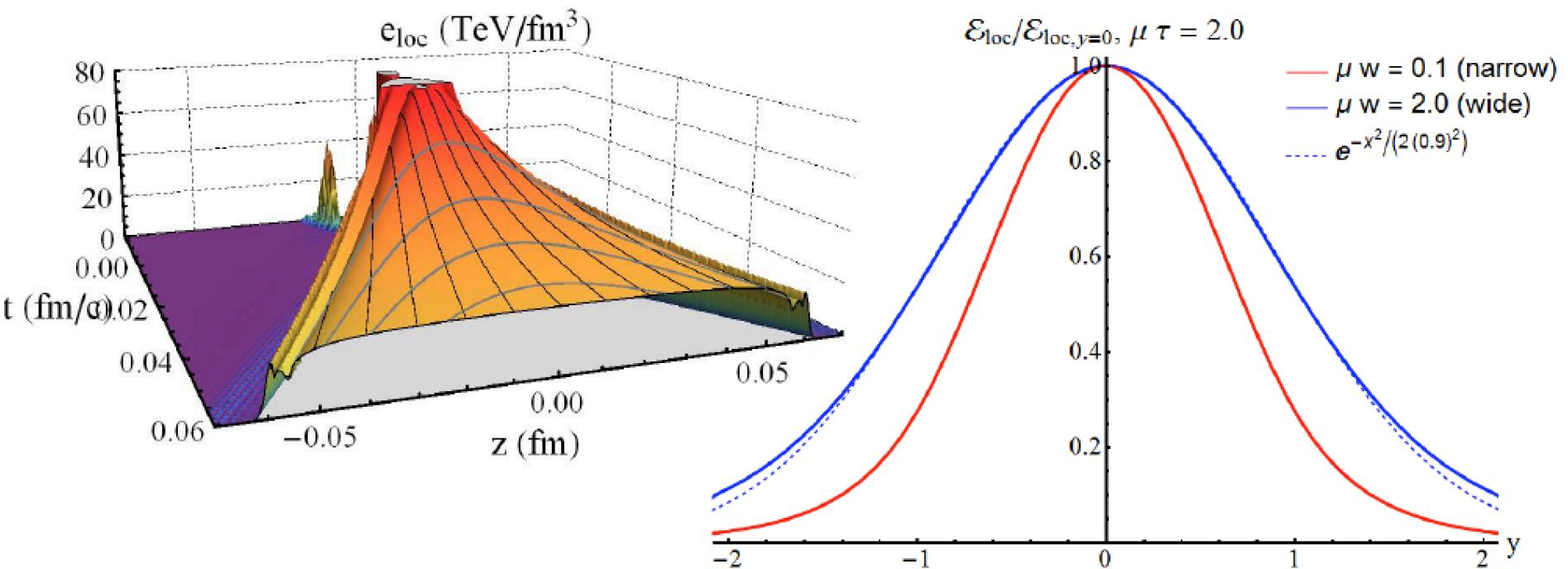
Dusling, Venugopalan, Gyulassy, Torrieri, et al.

- Thermalization, isotropization, what do you need for flow?

**Bozek, Schee, Schenke, Schlichting, Strickland**

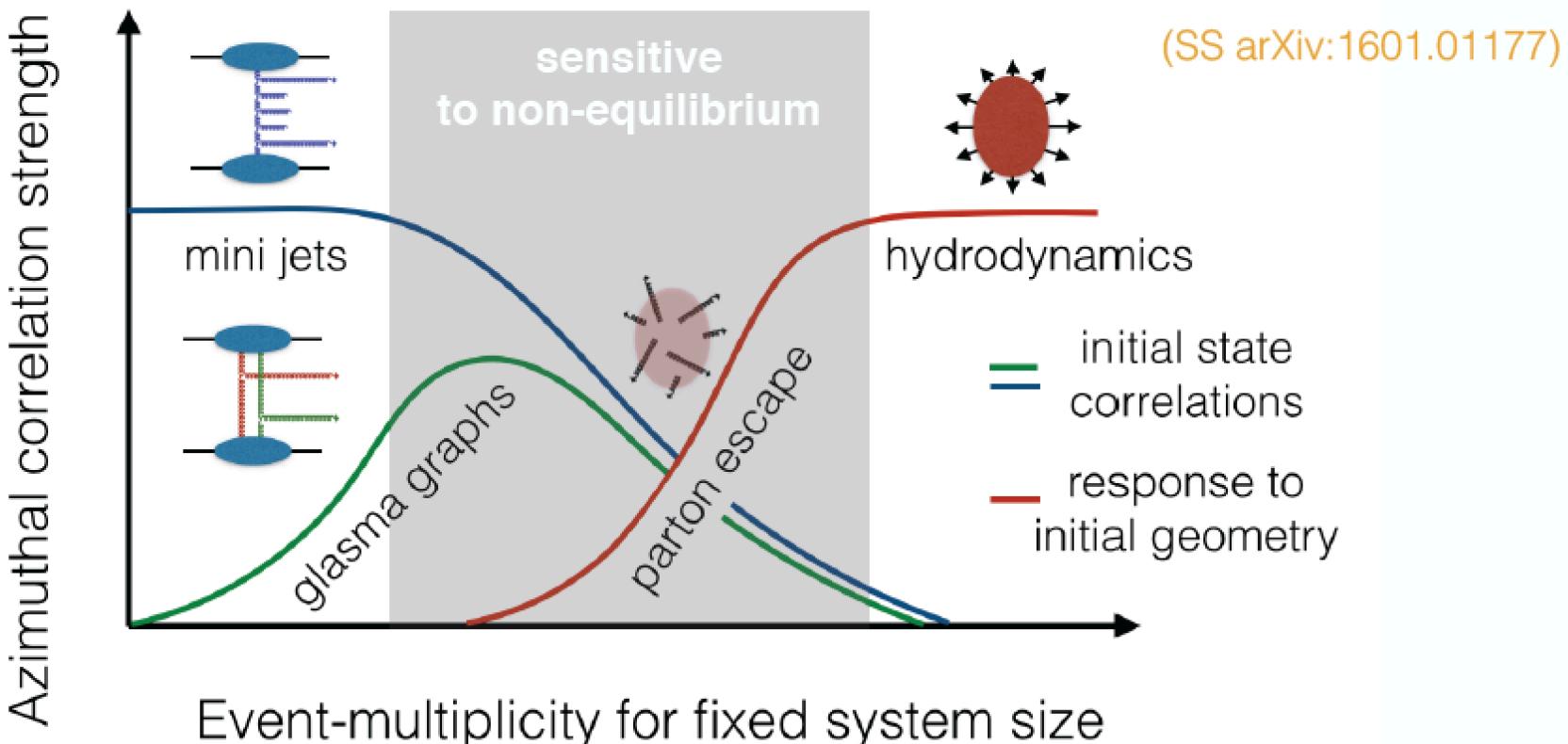
# A UNIVERSAL RAPIDITY PROFILE

Local energy density, flat in z, Gaussian-like in rapidity



Universal profile at high energies (compare with pQCD)

# Qualitative picture of correlations in small systems



-> Small systems provide a unique laboratory to probe early time dynamics.

**Soeren Schlichting**  
Rainer Fries  
Heikki Mäntysaari  
Mike Strickland

# How to Calculate Correlation Functions?

Ingredients:

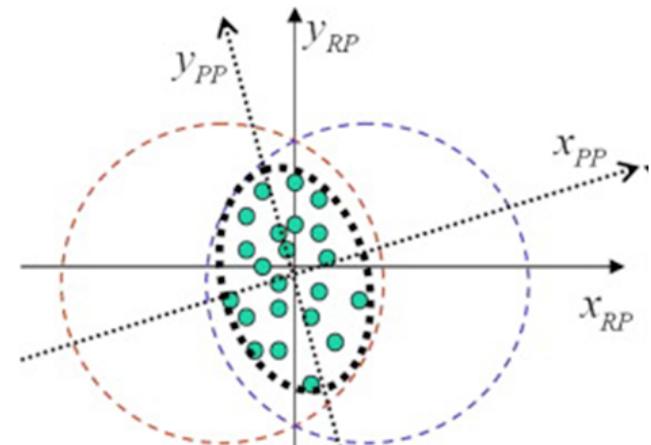
- Hydro, EOS
- Initial Conditions
- Dissipation, Transport Coefficients
- Fluctuations

Fluctuations are important:

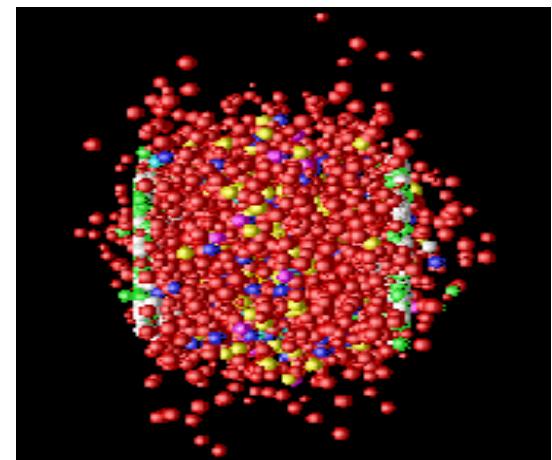
- dissipation without fluctuations wipes out correlated structure
- fluctuations seed phase separation

# Fluctuations in Hydrodynamics

- Initial Fluctuations
  - source: participants
  - most important



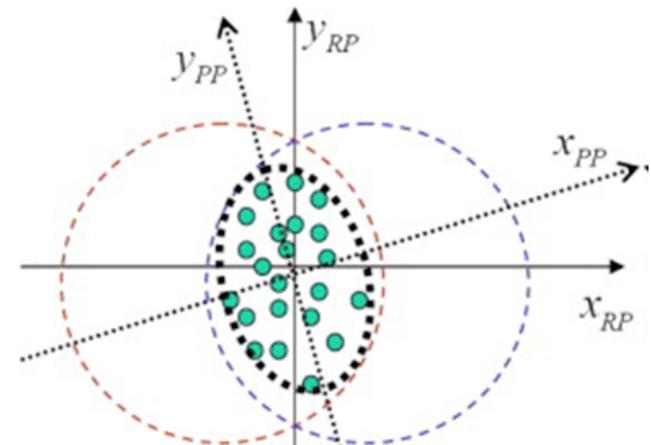
- Thermal noise in hydro
  - source: all particles
  - most important for observables that minimize shape effects



# Fluctuations in Hydrodynamics

- Initial Fluctuations

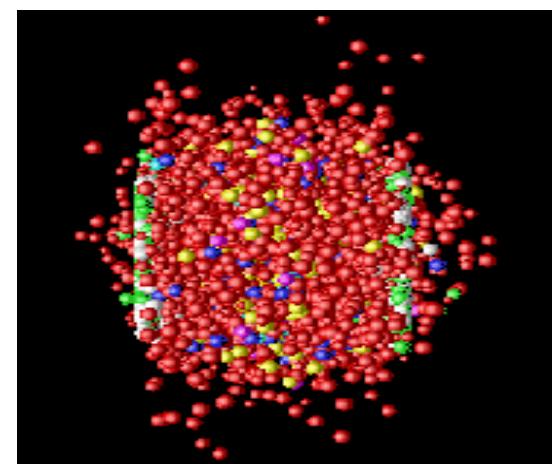
**Bozek, Schenke, Martinez**



- Thermal noise in hydro

**Gronqvist, Moschelli, Martinez,  
Young, Teaney**

Kapusta, Müller, Stephanov; Abdel-Aziz  
& Gavin; Murase, Hirano

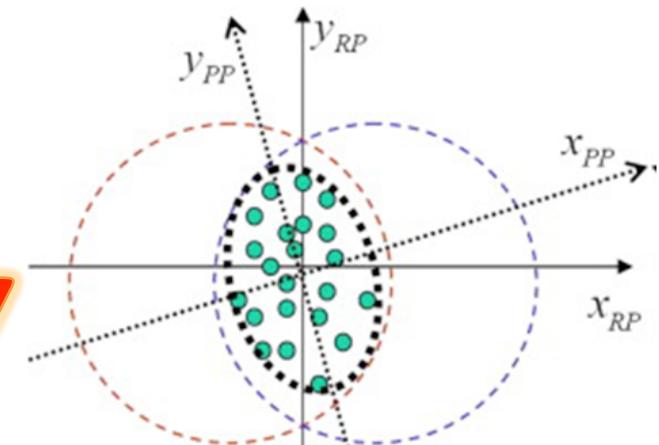


# Fluctuations in Hydrodynamics

- Initial Fluctuations

Bozek, Schenke, Martinez

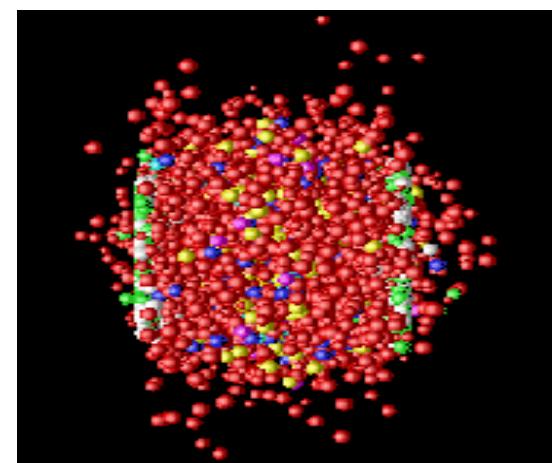
**EVERYBODY**



- Thermal noise in hydro

Grönqvist, Moschelli, Martinez,  
Young, Teaney

Kapusta, Müller, Stephanov; Abdel-Aziz  
& Gavin; Murase, Hirano

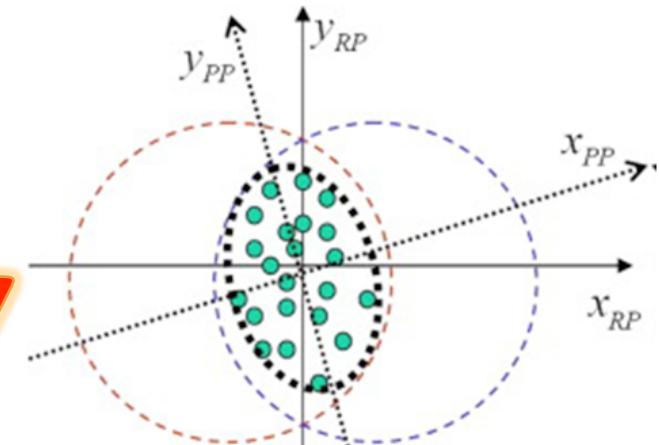


# Fluctuations in Hydrodynamics

- Initial Fluctuations

Bozek, Schenke, Martinez

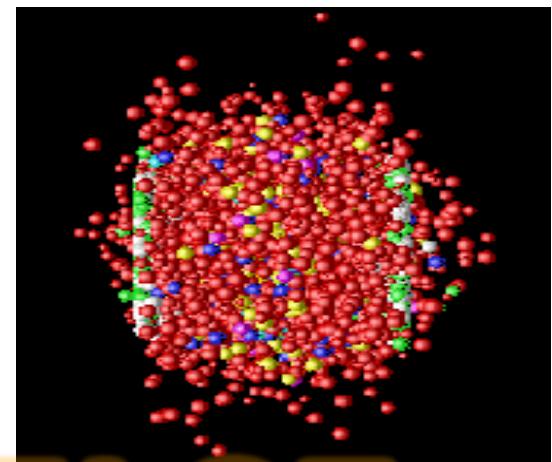
**EVERYBODY**



- Thermal noise in hydro

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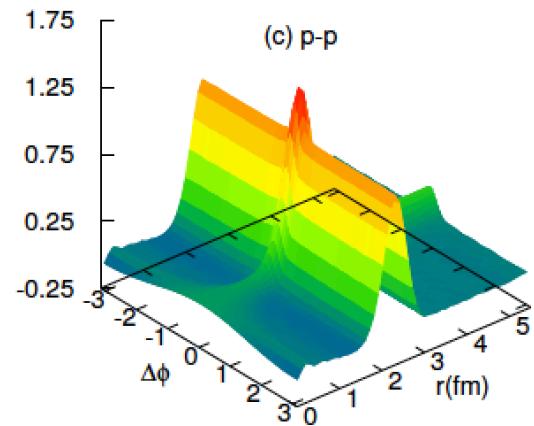


**EVERYBODY ELSE**

# What Can We Learn?

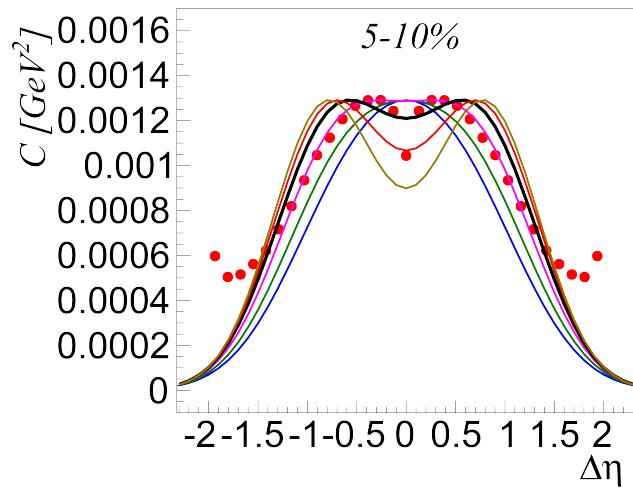
- Flow fluctuations  
and the Ridge

Young, Grönqvist



- $\eta$  and 2<sup>nd</sup> Order coefficient  $\tau_\pi$

Moschelli



- Diffusion Constants and Thermal Conductivity

Martinez, Noronha

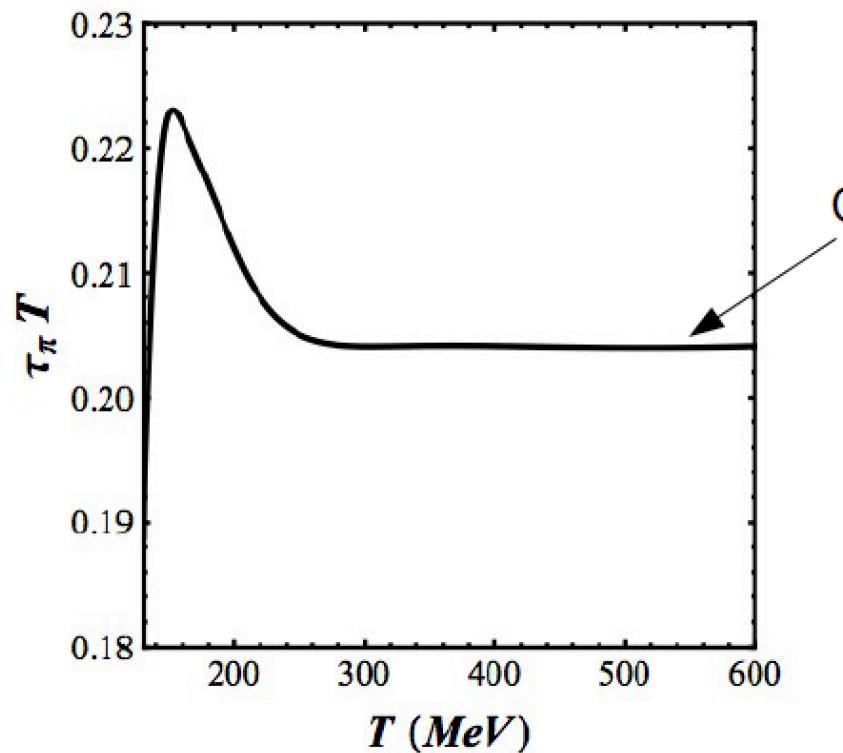
Stephanov and Shuryak; Abdel-Aziz & Gavin

## 2<sup>nd</sup> order transport coefficients

### The shear relaxation time

Jorge Noronha

Shear relaxation time has a small peak in the region  $T \sim 150 - 250$  MeV



Very different  
than kinetic  
theory calculations!

CFT (SYM) value

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

$$\tau_\pi T \sim 2\eta/s$$

kinetic theory     $\tau_\pi T \sim 5\eta/s$

# How to Measure? Correlation Functions

- rapidity correlations

$$S(\eta_1, \eta_2) = \text{pairs} - (\text{singles})^2$$

$$B(\eta_1, \eta_2) = (\text{singles})^2$$

- net-baryon balance function

Martinez, Noronha  
Pratt; Abdel-Aziz & SG

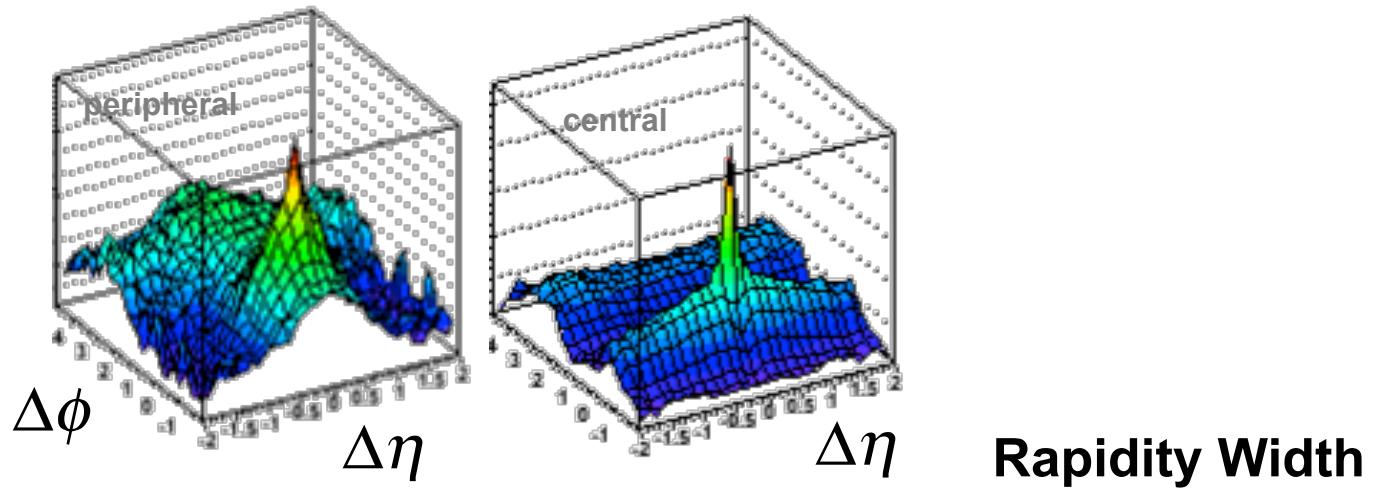
$$S_{net}(\eta_1, \eta_2) = \frac{S_{+-} - S_{++}}{\text{single}}$$

- $p_t$  covariance – momentum weighted  $S$

Moschelli

# STAR Pseudorapidity Correlations

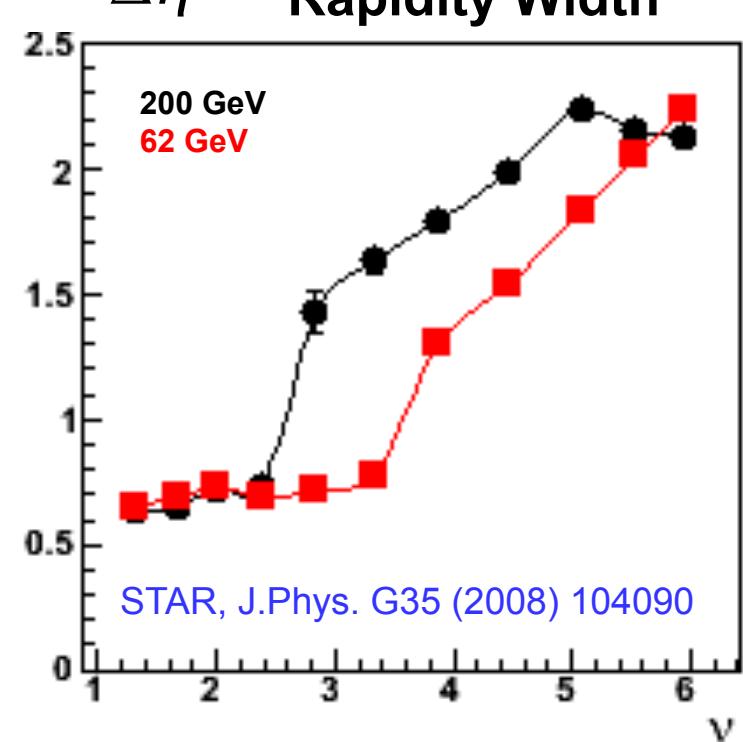
$$\frac{dN}{d\eta} \left( \frac{S}{B} - 1 \right)$$



Centrality

$$v \equiv \frac{\langle N_{bin} \rangle}{\langle N_{part} / 2 \rangle}$$

**Find:** rapidity width of central peak grows with increasing centrality



# Isolating Long Range Correlations

- Rapidity de-correlation of anisotropic flow

**Li, Huang**

**Abdelrahman, Wu**

- Pseudorapidity Correlations

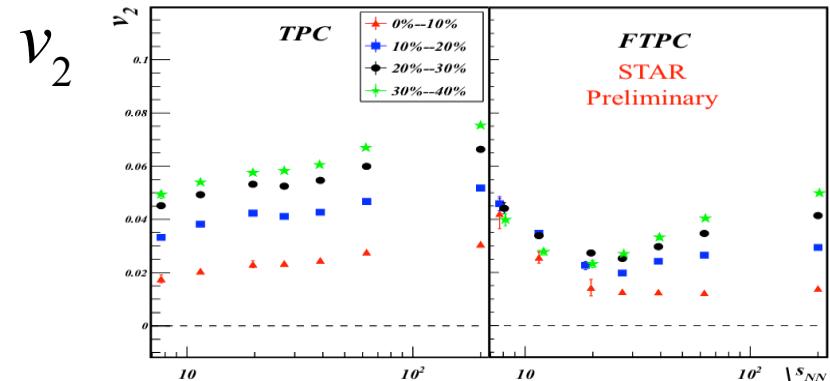
**Bzdak, Bozek, Brionowski**

**Li, Radhakrishnan, Ji**

# Isolating Long Range Correlations

- Rapidity de-correlation of anisotropic flow

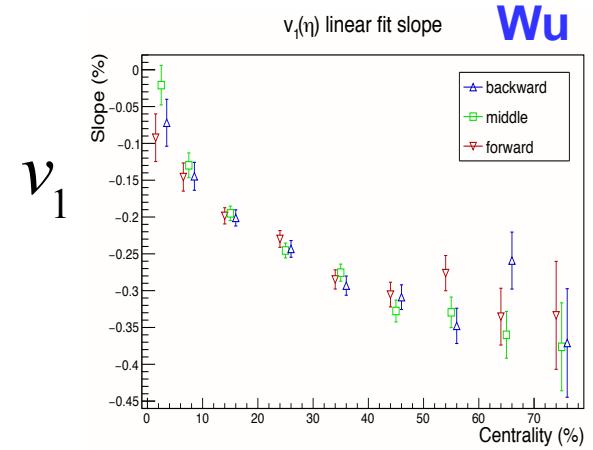
Abdelrahman



Li, Huang  
Abdelrahman, Wu

- Pseudorapidity Correlations

Bzdak, Bozek, Brionowski  
Li, Radhakrishnan, Ji



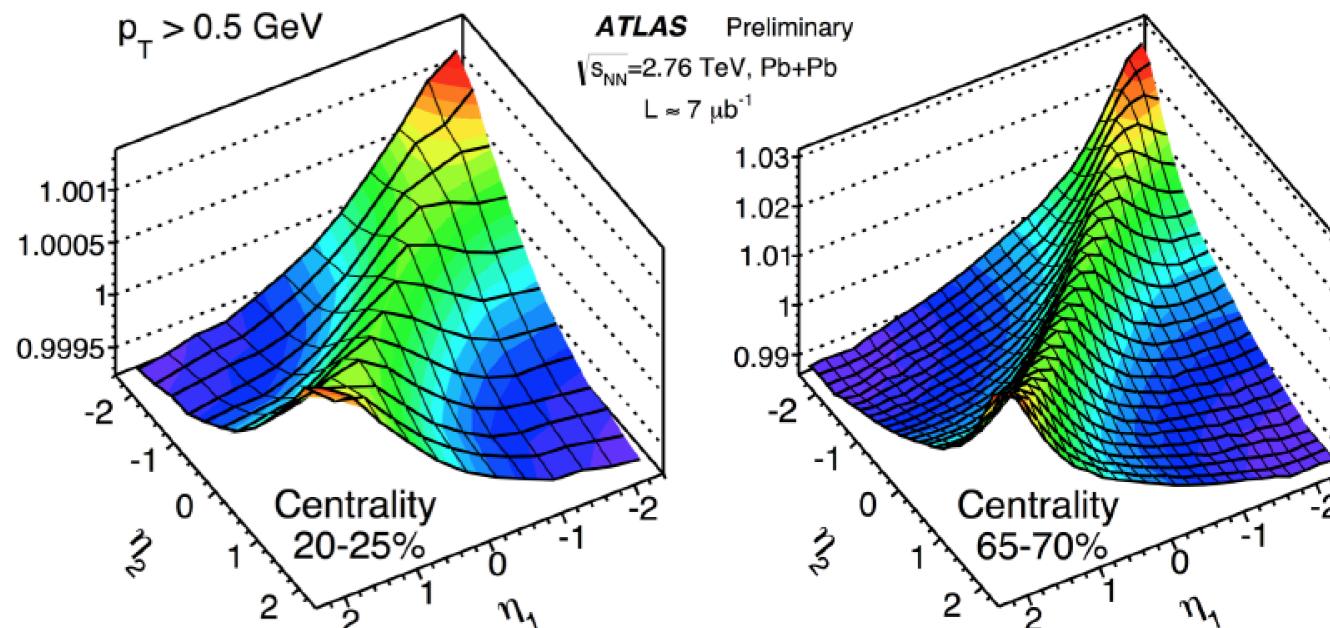
# Long Range Pseudorapidity Correlations

$$C(\eta_1, \eta_2) = \frac{\langle N(\eta_1, \eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle} = \frac{S(\eta_1, \eta_2)}{B(\eta_1, \eta_2)}$$

Bzdak  
Brionowski  
Bozek

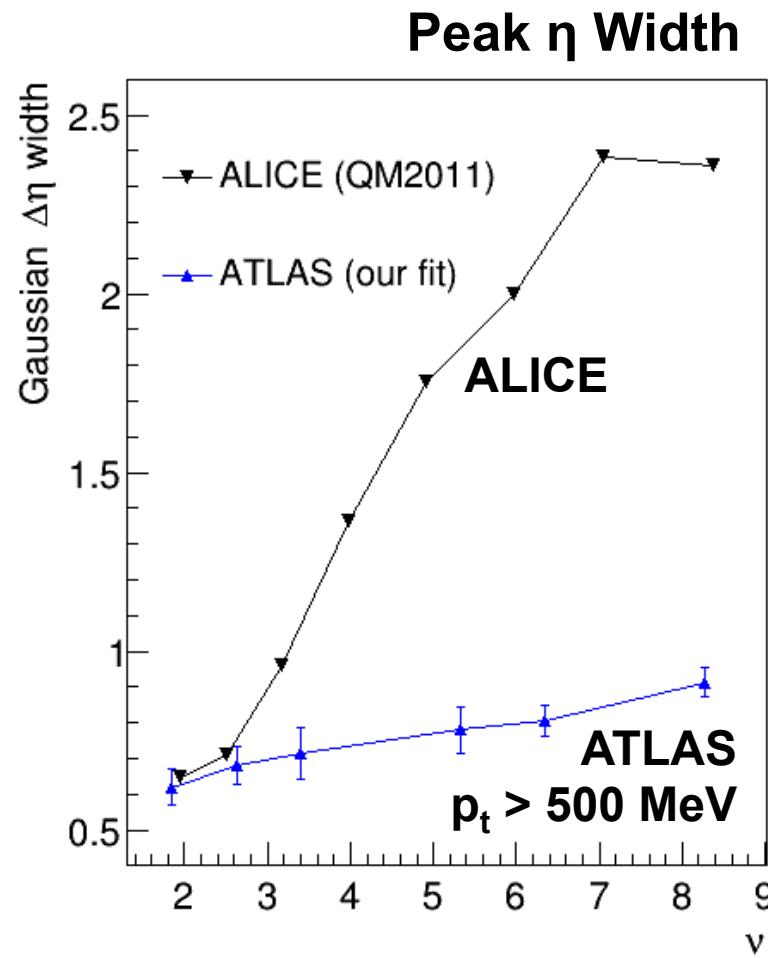
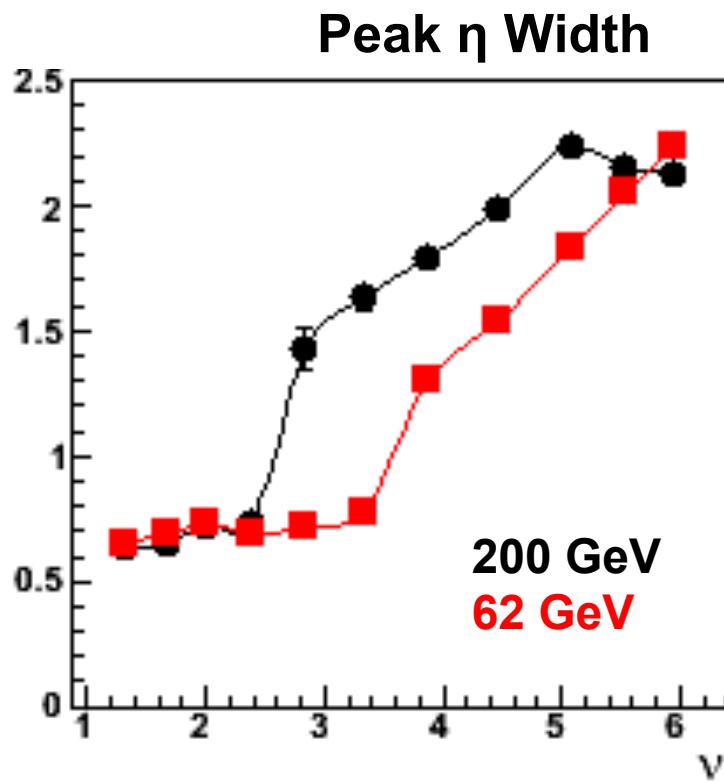
$$C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1)C_p(\eta_2)}, \quad C_p(\eta_1) = \int d\eta_2 C(\eta_1, \eta_2), \quad C_p(\eta_2) = \dots$$

$\eta_1$  and  $\eta_2$  – pseudorapidities of different hadrons



see also Ji's Talk

# Pseudorapidity Correlations



**Find:** rapidity width of central peak grows with increasing centrality

# Rapidity Asymmetry

Bzdak, Ji,  
Broniowski

$$\rho_{\text{event}}(y) = \langle \rho(y) \rangle \left[ 1 + a_0 + a_1 \frac{y}{Y} + \dots \right]$$

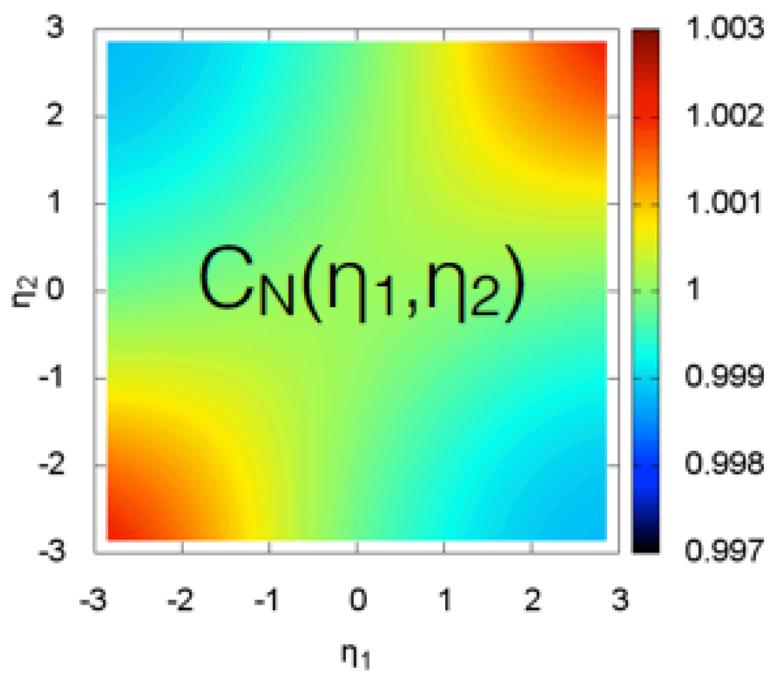
↑  
single particle distribution  
in an event

↑  
average single  
particle distribution

$a_0$  is rapidity independent fluctuation of fireball as a whole multiplicity distribution

$a_1$  is an event-by-event rapidity asymmetry

# Moments of the Correlation Function



Bzdak, Ji, Bozek  
Broniowski, Schenke

Expand in Legendre polynomials. The coefficients are given by

$$a_{n,m} = \int C_N(\eta_1, \eta_2) \frac{T_n(\eta_1)T_m(\eta_2) + T_n(\eta_2)T_m(\eta_1)}{2} \frac{d\eta_1}{Y} \frac{d\eta_2}{Y}$$

see: A. Bzdak, D. Teaney, Phys. Rev. C 87, 024906

J. Jia, S. Radhakrishnan, M. Zhou, arXiv:1506.03496, and ATLAS-CONF-2015-020,

# Causes of Asymmetry

Long range:

- Fluctuating flux tube length

**Bozek, Broniowski, Schenke**

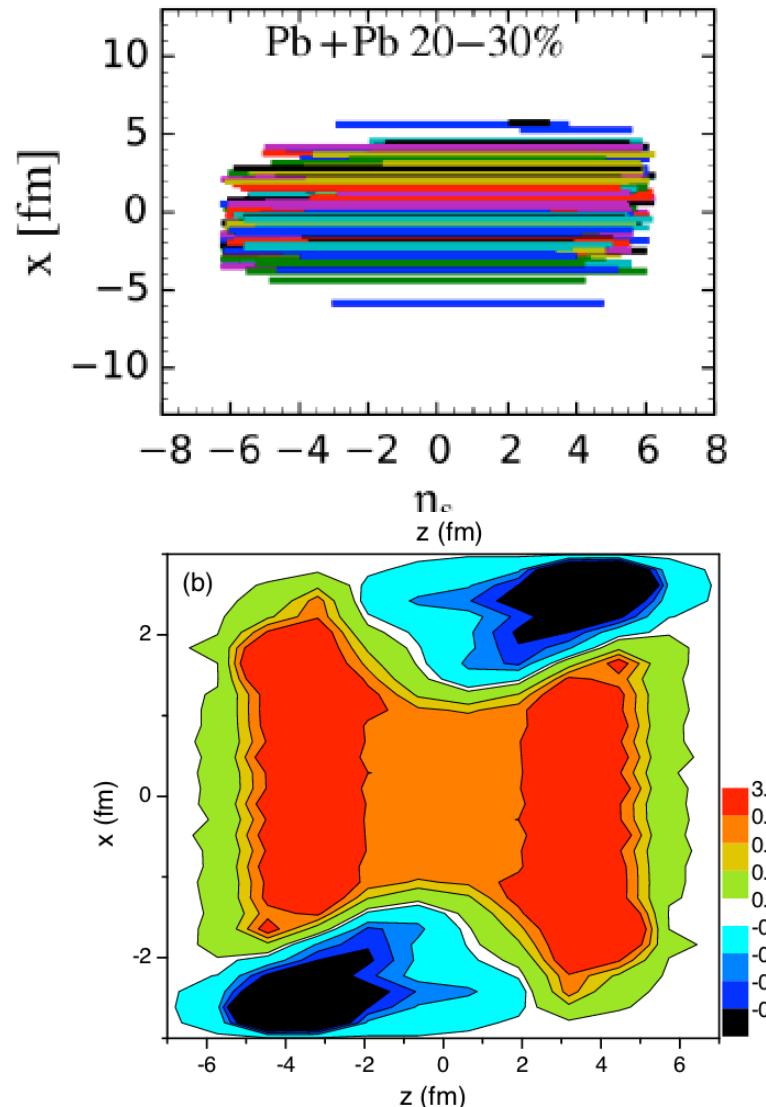
- Baryon stopping?

Beam energy scan

Short range:

- vorticity transfer to fireball

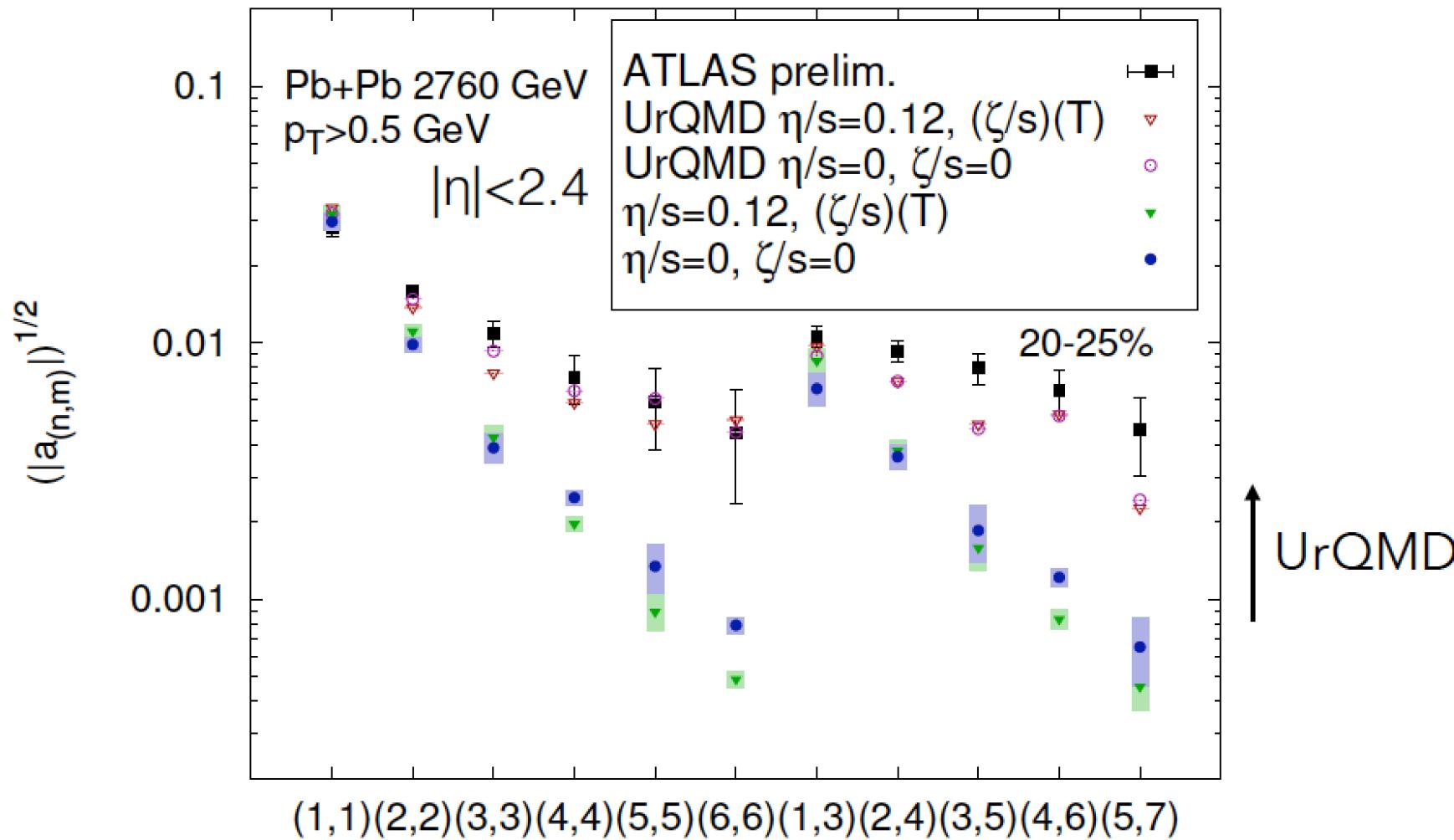
**Csernai, et al.**



# Couple to UrQMD: short range correlations matter

Gabriel Denicol, Akihiko Monnai, Sangwook Ryu, Bjoern Schenke, arXiv:1512.08231

Björn Schenke



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**Thanks to the organizers:**

**Adrian Dumitru, Kevin Dusling,**

**Akihiko Monnai, Paul Sorensen,**

**Jiangyong Jia,**

**and Prithwish Tripathy**

**Thanks to the speakers!**

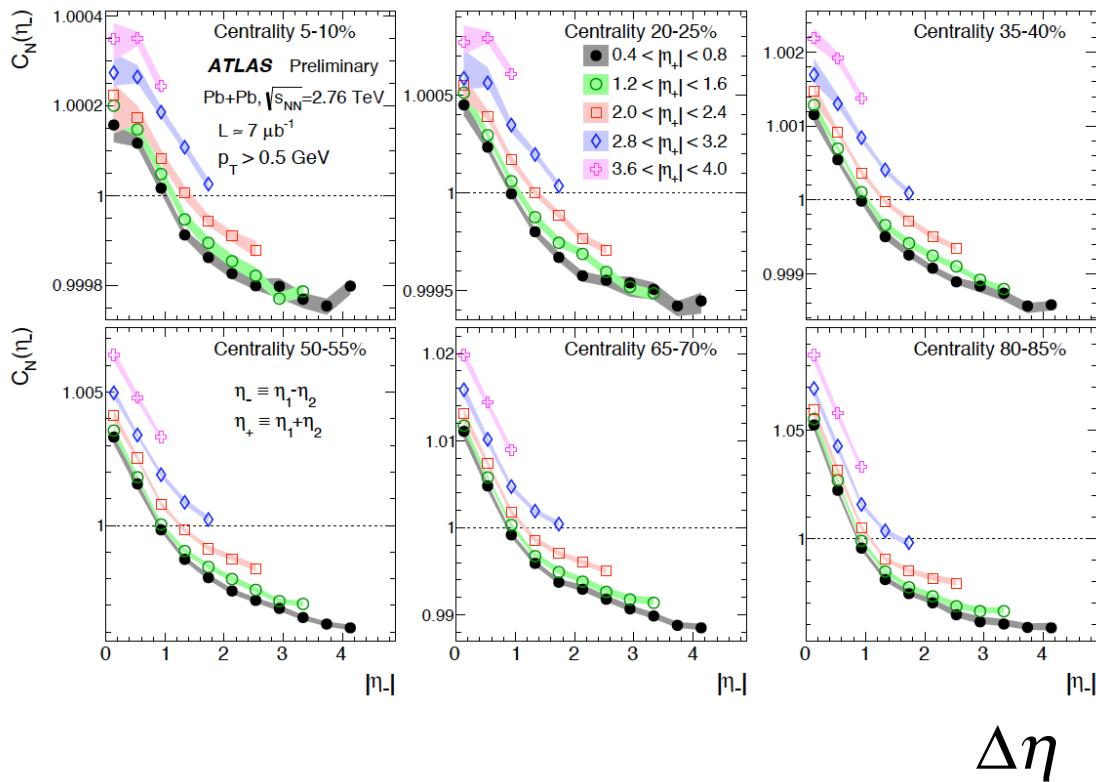
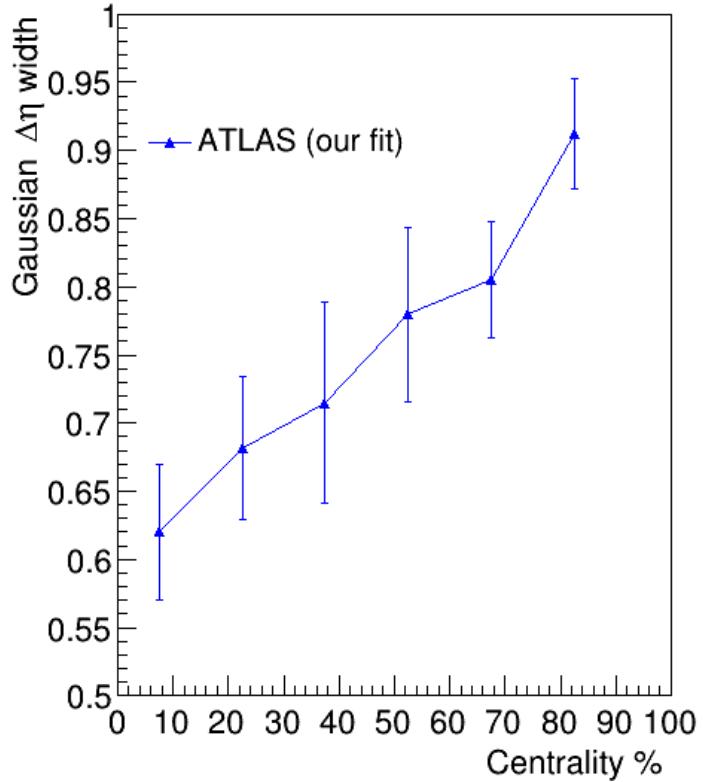
**Thanks to RBRC and especially Pam Esposito!**

**Safe home!!**



# ATLAS Pseudorapidity Correlations

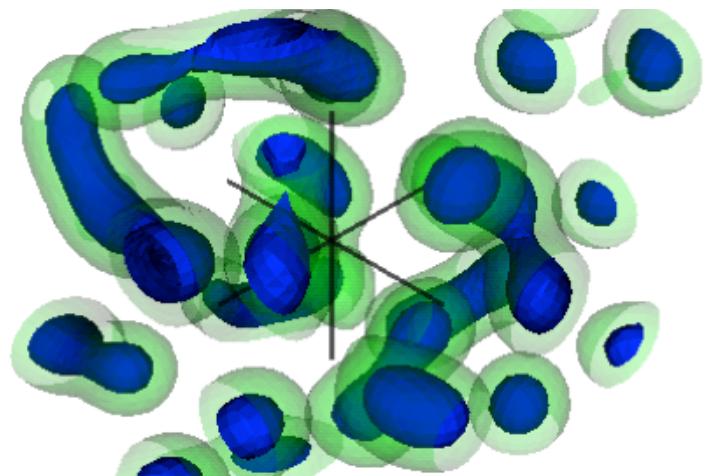
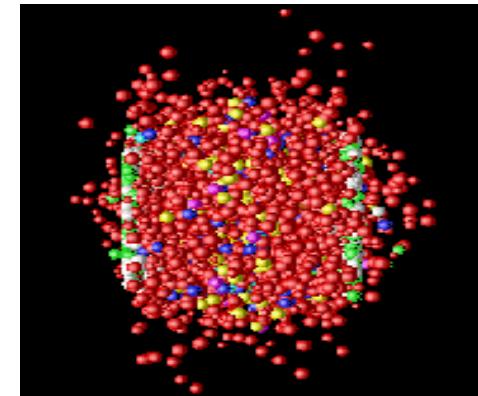
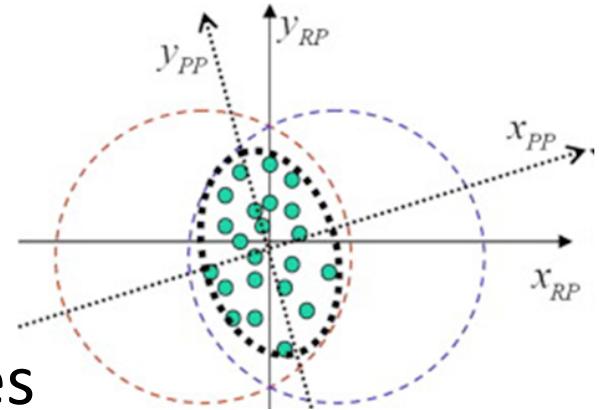
$$C_N = \frac{S}{B}$$



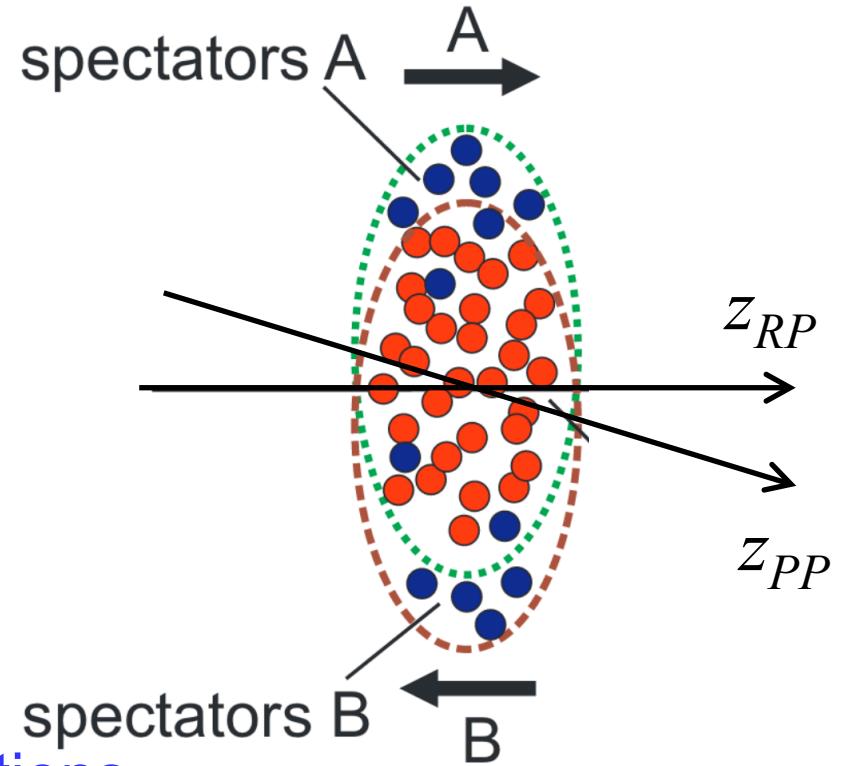
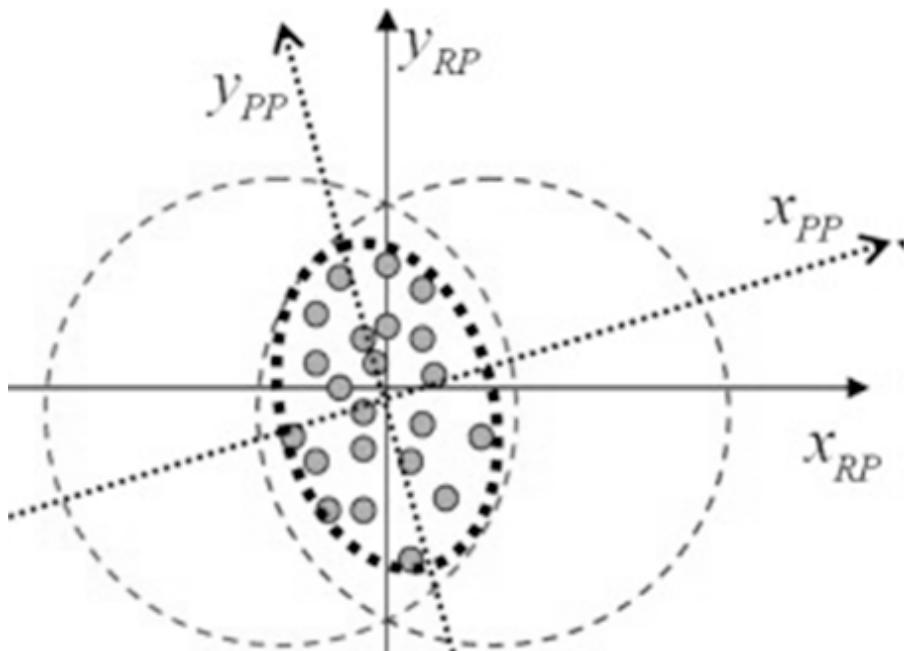
$\Delta\eta$

# Fluctuations in Hydro

- Initial Fluctuations
  - dominates top RHIC/LHC energies
- Thermal noise in hydro
  - important for observables that minimize shape effects
- Phase transition
  - *maybe* most important



# Longitudinal Geometry and Torque



**Bozek et al.** – flux tube fluctuations

Csernai, et al. – vorticity transfer to fireball

Low energy – baryon stopping

# Fluctuations in Hydrodynamics

- Initial Fluctuations

**Broniowski, Martinez, Bozek, Schenke**

- Thermal noise in hydro

**Gronqvist, Moschelli, Young, Teaney**

Kapusta, Müller, Stephanov; Abdel-Aziz & Gavin;  
Murase, Hirano

- Phase separation and critical phenomena

**Yi Yin**

Stephanov et al.; Bower & Gavin; Kapusta & Torres-Rincon; Randerup & Steinheimer; Herold, Nahrgang, Yan, Kobdaj